Self-Seeding Winter Cereal Cover Crops in Soybean

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ABSTRACT

Soil protection and nutrient scavenging benefits of cover crops have been widely reported. Nevertheless, adoption of cover crops in agronomic farming systems is low. Cover crop systems that do not require annual planting may increase adoption. The objectives of this study were to compare self-seeding and competitiveness of winter wheat (*Triticum aestivum* L.), triticale (x *Triticosecale* Wittmack), and rye (*Secale cereale* L.) using different planting configurations and management options while growing concurrently with soybean [*Glycine max* (L.) Merr.]. Cover crops were planted with two or four 19-cm rows between each 76-cm soybean row. A no-cover crop check treatment was also included for comparison. Cover crop species and species × management system interactions were not significant for seed production or soybean seed yield. Averaged across management system, cereals produced 10 656 and 4051 seeds m^{-2} in 2004 and 2005. The two-row band, no-chop treatment (2RBNC) produced the most seed (20 347 and 14 511 seeds m^{-2}) in 2004 and 2005, but also lowered soybean yield the greatest (45 and 40%). The four-row treatment with a late glyphosate band (4RLB) was the least competitive and yielded 3114 and 3717 kg ha^{-1} compared to 4019 and 4391 kg ha^{-1} in the check. Wheat had the greatest self-seeding, averaging about 31% of the original plant density. The four-row treatment without a glyphosate band (4RNB) could be used in organic production systems, although additional research is needed to develop less competitive self-seeding systems for conventional production systems.

The benefits of cover crops have been widely reported (Hartwig and Ammon, 2002; Sarrantonio and Gallandt, 2003; Snapp et al., 2005). Nevertheless, cover crop adoption in agronomic farming systems is low. In the northern USA, producers are often harvesting cash crops during the ideal cover crop planting period. Furthermore, the short-term costs associated with cover crops are difficult for producers to justify when profit margins are narrow. Reddy (2003) reported a net return for no-tillage soybean with a rye cover crop at \$29 ha^{-1} compared with 84 and \$87 ha^{-1} for conventional and no-tillage without a rye cover crop. These treatments yielded similarly, but the added costs for rye seed, planting, and dessication lowered the profitability compared to the standard no-cover crop system.

Innovative cover crop management systems are needed to reduce costs and maintain the same level of ecosystem benefits. Self-seeding legume cover crop systems are an example of an innovative approach relying on natural processes to reduce input costs and provide environmental protection from agricultural production. Ranells and Wagger (1992) reported that crimson clover (*Trifolium incarnatum* L.) successfully reseeded each year during their 3-yr study and that corn (*Zea mays* L.) grain yield was only marginally affected in 1 of 3 yr. They concluded that under adequate moisture conditions, a 50% dessicated strip can maximize clover N contribution, but a 75% strip-width can minimize potential competition with corn for water. Boquet and Dabney (1991) evaluated legume species for their effectiveness at reseeding and reported that crimson and subterranean (*Trifolium subterraneum* L.) clovers and big flower vetch (*Vicia grandiflora* Scop.) all reseeded before 21 April, berseem clover (*Trifolium alexandrinum* L.) reseeded before 13 May, and arrowleaf clover (*Trifolium vesiculosum* Savi.) did not reseed in a grain sorghum system in northeastern Louisiana.

Interest in legume reseeding systems was focused primarily on the N contribution from the legume to reduce N costs for subsequent crops with high N demand. Winter cereal cover crops do not offer the same potential for offsetting N costs, but do protect the soil, increase organic matter, and cycle nutrients (Hartwig and Ammon, 2002; Sarrantonio and Gallandt, 2003; Snapp et al., 2005). Successful self-seeding winter cereal cover crop systems must not excessively compete with the cash crop. Results from relay-intercropped soybean in winter wheat in Missouri found that soybean yield, averaged across 3 yr, was reduced 12% compared with a no-wheat full-season soybean planted in 80-cm row widths when wheat was at Feekes growth stage 10.3 and no N was added (Reinbott et al., 1987).

In self-seeding winter cereal systems where management of the cereal grain is not dependent on grain yield, it may be possible to reduce yield loss further. Singer and Kohler (2005) reported from 30 to 60% yield loss in soybean using mechanical control to suppress a rye cover crop at second node-, boot-, and anthesis growth stages. In their study, the four rows of rye planted between each 76-cm soybean row were highly competitive with soybean. Reducing the number of rows of cover crops spatially and temporally and using different winter cereals may provide more viable management options for producers, yet still provide the desirable ecosystem benefits. The objectives of this study were to: (i) compare growth and seed production of winter wheat, triticale, and rye cover crops using different planting configurations and management options while growing concurrently with soybean; (ii) quantify the competition

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Published in Agron. J. 99:73–79 (2007).
Cropping Systems
doi:10.2134/agronj2006.0032

Abbreviations: DM, dry matter; 4REB, four-row, early band treatment; 4RLB, four-row treatment with a late glyphosate band: 4RNB, four-row treatment without a glyphosate band; 2RB, two-row band treatment; 2RBNC, two-row band, no-chop treatment.

effects on soybean yield and yield components; and (iii) determine the ability of the cover crops to self-seed.

MATERIALS AND METHODS

Field studies were conducted at the Agricultural Engineering Research Center in Boone County, IA (42°01′ N, 93°45′ W; 341 m above sea level) from September 2003 through September 2005. The soil type was a Spillville loam (Fine-loamy, mixed, superactive, mesic Cumulic Hapludolls). The research area was planted to corn in the spring of 2003 and 2004 with grain harvest occurring on 17 Sept. 2003 and 27 Sept. 2004. Seedbed preparation following corn harvest included stalk shredding and a single pass with a tandem finishing disc set to operate at a depth of approximately 8 cm. Soil test levels in the surface 20-cm soil depth in 2004 were: 17 mg kg^{-1} P, 80 mg kg^{-1} K, and a pH of 6.6; and in 2005 were 20 mg kg^{-1} P, 115 mg kg^{-1} K, and a pH of 6.5. In March of 2004 and 2005, 35, 35, and 66 kg ha^{-1} N, P, and K were surface applied.

The experimental design was a randomized complete block with treatments arranged as a split-plot with four replicates. Cover crop species main plots were randomly assigned to winter rye (‘Rymin’), wheat (‘Karl 92’) and triticale (‘Décor’ in 2003 and ‘Kitaro’ in 2004). Décor seed was unavailable in 2004, therefore Kitaro was selected because it had a similar height and anthesis date. Cereals were selected for low height and an early anthesis date to minimize competition with soybean for light and to minimize delaying soybean planting. Cover crops were planted at 2 470 000 seeds ha^{-1} on 25 Sept. 2003 and 9 Oct. 2004 using a Marliss (Marliss Division/Sukup Manufacturing Co., Jonesboro, AR) grain drill with 19-cm row widths. Subplot treatments were cover crop management systems (Table 1) and a no-cover crop check. On 15 Oct. 2003 and 8 Nov. 2004 stand density was measured by counting all the plants in a 2.3-m^2 area in each subplot.

On 23 Apr. 2004 and 10 May 2005 glyphosate [*N*-(phosphonomethyl)glycine] (Roundup WeatherMax, Monsanto, St. Louis, MO) was applied to the four-row, early band (4REB) treatment in a 25-cm wide spray band centered over the soybean row at a rate of 1.1 kg a.i. ha^{-1} in solution with 68 L ha^{-1} of water. This application eliminated the two cover crop rows, one on each side of the future soybean row. At the time of herbicide application the mean Feekes growth stage (Zadoks et al., 1974) for the three species was 5.0.

Mechanical control was applied on 11 May 2004 and 21 May 2005 using a Buffalo (Fleischer Manufacturing, Columbus, NE) rolling stalk chopper to all treatments except the check and 2RBNC. This operation reduced cover crop height from about 45 cm to approximately 15 cm. Feekes growth stages before this operation were 10.3, 10.1, and 8.0 for rye, triticale, and wheat, respectively. Our goal was to time the operation to produce regrowth to obtain seed production. Ashford and Reeves (2003) reported 81 and 74% control of wheat and rye using a roller-crimper at anthesis and 95% control at the soft dough growth stage. To avoid confounding with soybean planting date and regrowth of the cover crops, all species were controlled on the same day.

Asgrow Brand ‘AG2107’ soybean was planted no-tillage on 17 May 2004 and 24 May 2005 at 445 000 seeds ha^{-1} in 76-cm rows. A glyphosate band was applied to the 4RLB treatment on 3 June 2004 and 9 June 2005, while a second glyphosate band application was applied to the 4REB on 22 June 2004 and 20 June 2005. The two-row band (2RB) and 2RBNC treatments only received one glyphosate band application. On 18 July 2005, glyphosate was broadcast on all plots at a rate of 1.1 kg a.i. ha^{-1} in solution with 68 L ha^{-1} of water to minimize weed seed production. Check treatments were maintained weed free for the entire growing season with additional glyphosate and hand weeding as necessary.

Cover crop shoot dry matter (DM) was collected on 10 May 2004 and 20 May 2005 from one 0.5-m^2 area (two rows, 0.38 m wide by 1.31 m long) in each subplot. All DM samples were clipped at the soil surface and dried at 70°C in a forced-air oven until a constant weight was achieved. On 17 May 2004 and 24 May 2005, gravimetric soil water was determined from the 0- to 30-cm soil depth by collecting four soil cores (18-mm diam.) from the row zone in each subplot. Soil samples from each subplot were combined, weighed wet, and dried in a forced-air oven at 100°C until dry. Weed density was determined by counting all the weeds in a 2.3-m^2 area in each subplot on 4 June 2004 and 13 June 2005. Cover crop tiller density was determined by counting all tillers in a 0.5-m^2 area (two rows, 0.38 m wide by 1.32 m long) in each subplot on 8 June 2004 and 14 June 2005. Cover crop height was determined after final height was attained by measuring the distance from the soil surface to the spike tip of the tallest tiller on 10 plants in each subplot.

At cover crop maturity, a 0.5-m^2 sample (two rows, 0.38 m wide by 1.32 m long) was collected from each subplot to determine shoot DM, spike number, and seed number. All cover crop plant samples were collected from the two interior rows in each interrow. Samples were collected when cereal treatments reached Feekes growth stage 11.4. At the R8 growth stage (Ritchie et al., 1994) of soybean, plant height from the soil surface to main stem tip was measured on 10 plants in each subplot and soybean plant population density was measured by counting all plants in 6.1 m of the three interior rows of each subplot. A harvest sample was collected from a 0.76-m^2 area to determine pod number, seed number pod^{-1}, and weight per 100 seed. In 2004, seed yield was calculated from this sample because of contamination from cover crop seed during soybean combine harvest. In 2005, seed yield was calculated from the combine harvest of the interior three rows of each subplot. Subsamples were collected to determine the mass fraction of cover crop seed and subtracted to obtain soybean seed weight. Seed yield data were corrected to 130 g kg^{-1} moisture. Cover crop self-seeding plant density was obtained by counting all of the plants in a 2.3-m^2 area in each subplot on 11 and 2 Nov. 2004 and 2005.

Daily rainfall and air temperature were recorded at a weather station about 3 km from the experimental site and presented by month for each growing season (Table 2). Statistical analysis was conducted using analysis of variance with block and block by species as random effects and cereal species and management system as fixed effects. Weed density

Table 1. Cover crop treatment description and control dates.

	Mechanical control date‡		Glyphosate band date§	
Treatment†	**2004**	**2005**	**2004**	**2005**
Check	–	–	–	–
Four-row, early band (4REB)	**11 May**	**21 May**	**23 Apr. and 22 June**	**10 May and 20 June**
Four-row, late-band (4RLB)	**11 May**	**21 May**	**3 June**	**9 June**
Four-row, no-band (4RNB)	**11 May**	**21 May**	–	–
Two-row band, no-chop (2RBNC)	–	–	**22 June**	**20 June**
Two-row band (2RB)	**11 May**	**21 May**	**22 June**	**20 June**

† Two or four 19-cm rows between each 76-cm soybean row.
‡ Mechanical control using a single pass with a rolling stalk chopper. Mean Feekes growth stages on 11 May 2004 and 21 May 2005 were: rye, 10.3; triticale, 10.1; and wheat, 8.0.
§ Glyphosate was applied in a 25-cm band over the soybean row.

Table 2. Monthly 2004 and 2005 growing season rainfall and air temperature near Ames, IA, and the 30-yr mean (1975–2004) for NWS COOP (National Weather Service Cooperator) site Ames 8SW.

	Rainfall			Air temperature		
Month	2004	2005	Mean	2004	2005	Mean
	mm			°C		
Apr.	61	82	88	11.6	12.8	10.2
May	208	111	112	16.7	15.6	16.4
June	91	124	124	20.0	23.3	21.3
July	50	104	113	22.2	24.4	23.4
Aug.	132	172	114	19.4	22.2	22.0
Sept.	34	111	76	20.0	20.6	18.1

data were square root transformed. Mean separation was accomplished using Fisher's protected LSD at $P = 0.05$.

RESULTS AND DISCUSSION

Analysis across year revealed year effects and interactions, so data are presented by year. Data are presented for species and management system main effects except for fall self-seeding plant density, because few species × management system interactions were detected. Only a cereal spike density interaction occurred in both years. The other three interactions will be discussed in the text in the appropriate section. In 2003, wheat density (147 plants m^{-2}) was greater than triticale and rye (113 plants m^{-2}), while wheat (157 plants m^{-2}) was greater than triticale (138 plants m^{-2}) and greater than rye (124 plants m^{-2}) in 2004. In 2003, the two-row treatments had greater stand density (137 plants m^{-2}) than the four-row treatments (116 plants m^{-2}), but no difference in stand density between two- and four-row treatments was detected in 2004 (139 plants m^{-2}).

Early Season Measurements

Cover crop DM before soybean planting was greater for rye (566 g m^{-2}) compared with wheat and triticale (443 g m^{-2}) in 2004 (Table 3). These differences in DM production were not reflected in soil water content differences among species. In 2005, rye (598 g m^{-2}) had greater DM production than wheat (437 g m^{-2}), but was similar DM to triticale (504 g m^{-2}). Similarly, no differences in soil water content were detected among species. Using fall plant density as a covariate in the analysis of early season DM was not significant either year. Among cover crop management systems, DM production was greater for the 2RBNC and 2RB (550 and 640 g m^{-2}) in 2004 and 2005 compared with the four-row treatments (439 and 429 g m^{-2}). Westgate et al. (2005) reported rye DM of 604 and 564 g m^{-2}, when mechanical control occurred at anthesis during two growing seasons. In 2004, the check and 4RLB treatments had higher row-zone soil water content compared with the 4REB and 4RNB treatments. In 2005, no soil water content differences were detected. In 2004, soil water measurement occurred on 17 May, and only 35 mm of the monthly 208 mm was recorded. April rainfall in 2004 was also 31% below the 30-yr mean. The expectation of the 4REB treatment was to preserve soil water in the row zone for soybean. In 2004, the 4REB had lower soil water content than the 4RLB treatment. These results indicate that soil surface cover by the cover crop was more important than soil water use by the cover crop for conserving soil water during early soybean growth.

Competition for light was also a concern in these treatments. Westgate et al. (2005) reported that rye intercepted 11 and 13% of photosynthetically active radiation in late July, when rye mechanical control occurred at anthesis. Reinbott et al. (1987) reported that competition for light in relay-intercropped soybean with winter wheat lowered soybean grain yield. Consequently, we used a rolling stalk chopper in all cover crop treatments except the 2RBNC to minimize light competition. Cover crop height after this operation was about 15 cm across species and management systems.

Tiller density of regrowth was higher in wheat than triticale and rye in both years (Table 3). Tiller density was greater in the 2RBNC compared with all treatments in 2004 except the 2RB and all treatments in 2005. Both two-row treatments probably had greater tiller density than the 4RNB treatment because of greater light transmittance to the plant basal region. Westgate et al. (2005) reported no difference in rye tiller density when mechanical control occurred at the second node, boot, and anthesis growth stages (126 tillers m^{-2}) in 2002 and

Table 3. Mean cover crop shoot dry matter (DM), row-zone soil water content in the surface 30 cm before soybean planting, and cover crop tiller and weed density in early June 2004 and 2005 for cover crop species and management systems.

	DM		Soil water		Tiller density		Weed density§	
Factor	2004	2005	2004	2005	2004	2005‡	2004	2005
	g m^{-2}		kg kg^{-1}		no. m^{-2}			
Species								
Wheat	441b†	437b	0.215a	0.249a	765a	292	2.61a	3.31a
Triticale	445b	504ab	0.206a	0.254a	376b	116	1.42a	2.54a
Rye	566a	598a	0.210a	0.249a	401b	149	2.10a	1.34a
Management system¶								
Check	–	–	0.218ab	0.257a	–	–	–	–
Four-row, early band (4REB)	458b	451b	0.201c	0.239a	443bc	74	1.44a	1.49b
Four-row, late-band (4RLB)	413b	397b	0.221a	0.262a	504b	111	1.95a	2.20b
Four-row, no-band (4RNB)	447b	438b	0.201c	0.241a	419c	50	1.60a	1.46b
Two-row band, no-chop (2RBNC)	552a	644a	0.205bc	0.247a	602a	587	2.64a	3.31a
Two-row band (2RB)	548a	635a	0.214abc	0.244a	602a	107	2.55a	3.52a

† Means followed by the same letter within a column and factor are not different at $P = 0.05$.
‡ A species × management system interaction was detected.
§ Means are square root transformed.
¶ Two or four 19-cm rows between each 76-cm soybean row and mechanical control in all treatments except the 2RBNC using a rolling stalk chopper.

higher tiller density in 2003 between the second node and anthesis treatments (80 vs. 61 tillers m^{-2}). A species × management system interaction for tiller density was observed in 2005. The interaction occurred because tiller density in the 2RB treatment in wheat and rye were similar (141 tillers m^{-2}), and were both greater than the 2RB in triticale (41 tillers m^{-2}).

Weed densities in early June in each year were similar for species and most management systems (Table 3). In 2005, both two-row treatments had greater weed density than the four-row treatments. Presumably, this difference occurred because of greater light transmittance to the soil surface. In 2004, weed density was dominated by lambsquarters (*Chenopodium album* L.) and smartweed (*Polygonum pensylvanicum* L.), while only lambsquarters was dominant in 2005.

Cover Crop Growth

Cover crop DM at maturity was similar across species and averaged 630 and 370 g m^{-2} in 2004 and 2005 (Table 4). The 2RBNC treatment had greater DM than all other treatments both years. The 2RB treatment had greater DM than the 4REB treatment both years. Among the four-row treatments, differences in DM were limited to the 4REB and 4RLB in 2004. The 2RB treatment probably had greater DM than the 4RNB treatment because of less competition for resources. Although shields were used when the herbicide bands were applied, glyphosate drift may have affected cover crop growth and DM in the 4REB treatment. This treatment may have been affected more because stem elongation had not occurred when the herbicide band was applied.

Species differences were observed for height (Table 4). At maturity, rye was 100 cm in 2004 compared with 73 and 63 cm for triticale and wheat. In 2005, a species × management system interaction was detected for cover crop height. Height of rye in the 2RB treatment (75 cm) was greater than all of the four-row treatments (67 cm), while these comparisons were similar in wheat and triticale. The 2RBNC treatment was the tallest in wheat (58 cm), triticale (86 cm), and rye (112 cm) in 2005.

A species × management system interaction was also detected in both years for spike density. In 2004, spike density was greater in the 2RB (1032 spikes m^{-2}) compared to 2RBNC (900 spikes m^{-2}) treatment in wheat. In triticale and rye, spike density was greater in the 2RBNC (499 and 675 spikes m^{-2}) compared with 2RB treatment (409 and 423 spikes m^{-2}). In 2005, spike density in wheat was similar in the 4REB, 4RLB, and 4RNB treatments (329, 398, and 319 spikes m^{-2}), but less than the 2RBNC (922 spikes m^{-2}). The 2RB (422 spikes m^{-2}) and 4RLB had similar spike density, both lower than the 2RBNC. In triticale, all treatments were similar (221 spikes m^{-2}) except the 2RBNC (458 spikes m^{-2}). In rye, spike density was similar in the 4REB and 4RNB (112 spikes m^{-2}), which was lower than the 4RLB and 2RB (226 spikes m^{-2}), which was lower than the 2RBNC (532 spikes m^{-2}).

Although an interaction was detected for spike density, seed density did not exhibit the interaction. Seed density was similar across species in 2004 and averaged 10 656 seeds m^{-2} (Table 4). In 2005, wheat seed density (5070 seeds m^{-2}) was greater than triticale and rye (3542 seeds m^{-2}). The greatest seed density occurred in the 2RBNC treatment both years. In 2004, similar seed production occurred in the 4RLB and 2RB treatments (9895 seeds m^{-2}), which was greater than the 4REB and 4RNB treatments (6574 seeds m^{-2}). In 2005, all of these treatments had similar seed production (1436 seeds m^{-2}), which averaged 90% lower than the 2RBNC treatment. The below-average rainfall and air temperature in June of 2004 may have contributed to the greater seed yield in 2004.

At the time of mechanical control, cover crop development stages ranged from the flag leaf just visible in wheat (Feekes 8.0), to first spikelet of the inflorescence just visible in triticale (Feekes 10.1), to one-half of the inflorescence emerged in rye (Feekes 10.3). The timing of the mechanical control favored regrowth of wheat, although no differences were detected either year for final DM yield and there were no species × management system interactions for final DM. Mechanical control of wheat at the earlier growth stage affected tiller density and spike density, which increased seed density

Table 4. Mean cover crop shoot dry matter (DM), spike and seed density, and height at maturity in 2004 and 2005 for cover crop species and management systems near Ames, IA.

Factor	DM		Spike density§		Seed density		Height	
	2004	2005	2004	2005	2004	2005	2004	2005¶
	g m^{-2}		no. m^{-2}				cm	
Species								
Wheat	686a†	393a	885	478	11345a	5070a	63b	41
Triticale	639a	406a	397	269	11153a	3664b	73b	60
Rye	566a	312a	459	242	9471a	3419b	100a	78
Management system‡								
Four-row, early band (4REB)	352d	95c	464	218	5999c	936b	71d	54
Four-row, late-band (4RLB)	467bc	159bc	636	281	9758b	1717b	74c	52
Four-row, no-band (4RNB)	374cd	109bc	491	212	7148c	1321b	75bc	51
Two-row band, no-chop (2RBNC)	1387a	1351a	691	638	20347a	14511a	94a	85
Two-row band (2RB)	573b	186b	621	299	10032b	1770b	78b	55

† Means followed by the same letter within a column and factor are not different at $P = 0.05$.
‡ Two or four 19-cm rows between each 76-cm soybean row and mechanical control in all treatments except the 2RBNC using a rolling stalk chopper.
§ Species × management system interactions were detected both years.
¶ A species × management system interaction was detected.

Table 5. Mean soybean harvest plant population density (PPD), seed yield (SY), shoot dry matter (DM), pod density (PODD), seed per pod (SPP), hundred seed weight (HSW), harvest index (HI), and plant height (PH) in 2004 for cover crop species and management systems near Ames, IA.

Factor	PPD	SY	DM	PODD	SPP	HSW	HI	PH
	no. m^{-2}	kg ha^{-1}	g m^{-2}	no. m^{-2}	no. pod^{-1}	g		cm
Species								
Wheat	35a†	3110a	500a	994a	2.01a	15.4a	0.59a	72a
Triticale	35a	3016a	487a	929a	2.04a	15.5a	0.59a	72a
Rye	33a	2947a	482a	916a	2.05a	15.3a	0.58a	73a
Management system‡								
Check	36ab	4019a	674a	1113a	2.22a	16.0a	0.56b	86a
Four-row, early band (4REB)	35ab	3215b	515b	1017ab	2.05b	15.3b	0.59a	73b
Four-row, late-band (4RLB)	38a	3114b	498b	979b	2.05b	15.2b	0.59a	72bc
Four-row, no-band (4RNB)	29c	2515c	412c	831c	1.98b	15.1b	0.58ab	67e
Two-row band, no-chop (2RBNC)	33bc	2227c	353c	762c	1.88c	15.3b	0.59a	68de
Two-row band (2RB)	36ab	3054b	487b	974b	2.01b	15.5ab	0.59a	70cd

† Means followed by the same letter within a column and factor are not different at $P = 0.05$.
‡ Two or four 19-cm rows between each 76-cm soybean row and mechanical control in all treatments except the 2RBNC using a rolling stalk chopper.

in 1 yr compared with triticale and rye. Using final cover crop DM as a covariate in the analysis for soybean yield and yield components was not significant either year for any variable.

Soybean Yield and Yield Components

Harvest plant population densities were similar across species in both years and generally lower in the more competitive 4RNB and 2RBNC treatments (Tables 5 and 6). In 2004, the 4RNB treatment had lower plant density (29 plants m^{-2}) than all other treatments (36 plants m^{-2}) except the 2RBNC (33 plants m^{-2}). In 2005, the check and 2RB treatments had greater plant density (37 plants m^{-2}) than the 2RBNC treatment, while the 4REB, 4RLB, 4RNB, and 2RB had similar plant density (33 plants m^{-2}). Final DM was similar across species in 2004 (490 g m^{-2}) and 2005 (592 g m^{-2}). The 4REB and 4RLB had similar DM both years. The 2RBNC had lower DM than the 2RB both years and the check had greater DM than the 4RNB both years. The 2RB had greater DM than the 4RNB only in 2004.

Cereal species had no effect on seed yield, while all management treatments yielded lower than the check both years. The 4REB and 4RLB had similar seed yield in 2004 (3165 kg ha^{-1}) and 2005 (3625 kg ha^{-1}), which was 21 and 17% lower than the check. The 2RBNC had 27 and 25% lower seed yield than the 2RB in 2004 and 2005. The 2RB and 4RNB treatments had similar seed yield in 2005, but the 2RB had 18% higher yield in 2004. Wallace et al. (1992) concluded that relay-intercropped soybean following wheat, when the period of overlap between wheat and soybean was relatively short, may not result in yield reductions. In our management systems, cover crops in the 2RBNC treatment matured earlier because no mechanical control occurred. In 2004 and 2005, averaged across species, the 2RNC treatment reached Feekes stage 11.4 on July 13 and 7 compared with about July 23 and 20 for the other treatments. Although the period of overlap between active cover crop growth and soybean was shorter in the 2RBNC, excessive shading to soybean limited light interception and probably had the greatest impact on lowering soybean seed yield.

The yield loss observed in this study was greater than expected. Reinbott et al. (1987) reported a 12% soybean grain yield reduction in their relay-intercropped system in wheat compared with full-season soybean when soybean was planted when wheat was at Feekes growth stage 10.3, no N was added, and soybean was planted in 80-cm row widths. Singer and Kohler (2005) reported a 30 to 60% yield reduction in a 2-yr study in Iowa using rye, averaged across mechanical control at the second node-, boot-, and anthesis-growth stages compared with a no-cover crop check. In their study, a skip-row system was not used. One explanation for the magnitude of the

Table 6. Mean soybean harvest plant population density (PPD), seed yield (SY), shoot dry matter (DM), pod density (PODD), seed per pod (SPP), hundred seed weight (HSW), harvest index (HI), and plant height (PH) in 2005 for cover crop species and management systems near Ames, IA.

Factor	PPD	SY	DM	PODD§	SPP	HSW	HI	PH
	no. m^{-2}	kg ha^{-1}	g m^{-2}	no. m^{-2}	no. pod^{-1}	g		cm
Species								
Wheat	33a†	3455a	585a	1079	1.92a	14.2a	0.50a	77b
Triticale	33a	3446a	568a	997	1.94a	14.3a	0.49a	76b
Rye	34a	3743a	624a	1126	1.95a	14.2a	0.50a	81a
Management system‡								
Check	38a	4391a	752a	1175	2.21a	14.4ab	0.50a	95a
Four-row, early band (4REB)	31bc	3532bc	585b	1047	1.99b	14.1bc	0.50a	76c
Four-row, late-band (4RLB)	32bc	3717b	623b	1109	1.98b	14.5a	0.51a	81b
Four-row, no-band (4RNB)	34bc	3535bc	602b	1106	1.96b	14.0c	0.50a	75c
Two-row band, no-chop (2RBNC)	30c	2626d	413c	894	1.61c	13.8c	0.47b	66d
Two-row band (2RB)	35ab	3488c	578b	1074	1.86b	14.5a	0.50a	76c

† Means followed by the same letter within a column and factor are not different at $P = 0.05$.
‡ Two or four 19-cm rows between each 76-cm soybean row and mechanical control in all treatments except the 2RBNC using a rolling stalk chopper.
§ A species × management system interaction was detected.

yield loss we observed compared with Reinbott et al. (1987) may have been the competitiveness of the cereal cultivars we selected. Identifying less competitive cereal cultivars may lower the soybean yield loss in self-seeding systems. Additional work could also explore cultivar selection and breeding of soybean to improve its competitiveness in systems with interspecific competition.

Species response was similar for seed pod^{-1} (2.03 and 1.94), g 100 seed^{-1} (15.4 and 14.2), harvest index (HI) (0.59 and 0.50) in 2004 and 2005, and pod density in 2004 (946 pods m^{-2}); but a species × management system interaction was detected for pod density in 2005 (Tables 5 and 6). The fewest seed pod^{-1} were found in the 2RBNC treatment in 2004 and 2005 (1.88 and 1.61). The 4REB, 4RLB, 4RNB, and 2RB had similar seed pod^{-1} in 2004 and 2005 (2.02 and 1.95), all lower than the check (2.22 and 2.21). In 2004, seed weight was similar among cover crop management treatments (15.3 g 100 seed^{-1}), while the check and 2RB had similar seed weight (15.8). In 2005, generally, the more competitive treatments (4RNB and 2RBNC) had lower seed weight. Harvest index was generally not sensitive to cover crop management, which indicates soybean altered assimilate partitioning to compensate for assimilate supply and sink demand. The species × management system interaction for pod density in 2005 occurred primarily because the 2RBNC treatment responded differently among species. In wheat, all treatments had similar pod density except the check (1218 pods m^{-2}) and 2RBNC (993 pods m^{-2}). In triticale, pod density in the 2RBNC (648 pods m^{-2}) was lower than all other treatments, but the 4RLB also had lower pod density (959 pods m^{-2}) than the 4REB (1164 pods m^{-2}). In rye, the 4REB (960 pods m^{-2}) had lower pod density than the 4RLB and 4RNB (1231 pods m^{-2}).

Fall Self-Seeding Densities

Self-seeding of all species and cover crop management systems occurred in the fall of 2004 and 2005. In 2004, wheat self-seeding exceeded triticale and rye (Table 7). Among management systems, the 2RBNC (53 plants m^{-2}) had the greatest self-seeding compared with the other management treatments (15 plants m^{-2}). These plant densities represent from 8 (4REB) to 38% (2RBNC) of the original fall densities, averaged across species. In 2005, a species × management system interaction was detected for self-seeding density. In wheat, the 4REB, 4RNB, and 2RBNC had similar densities (60 plants m^{-2}), all higher than the 4RLB and 2RB (35 plants m^{-2}). In triticale, the 2RBNC (58 plants m^{-2}) had greater self-seeding plant density than the rest of the treatments, which had similar densities (13 plants m^{-2}). In rye, the 2RBNC (49 plants m^{-2}) had greater self-seeding plant density than the rest of the treatments, which had similar densities (4 plants m^{-2}). Singer and Kohler (2005) reported similar fall self-seeding tiller densities for rye (23 tillers m^{-2}) when mechanical control occurred at the second node-, boot-, and anthesis growth stages in 1 of 2 yr. In the second year, treatment differences were detected, but tiller densities ranged from 11 to 4 tillers m^{-2} for control at the second node-, boot- and anthesis growth stages. Because seed number was similar between rye and triticale both years, lower seed quality of rye or the physical process of self-seeding may have reduced the efficiency of self-seeding in rye in this study.

These plant densities represent from 18 to 44% in wheat, 5 to 40% in triticale, and 3 to 43% in rye of the original fall densities. The earlier mechanical control of wheat in 2005 probably contributed to the greater self-seeding. However, the results also indicate cover crop seed production may not be the limiting factor. Assuming that the seeds produced were viable, seed dispersal may be the limiting factor. For conventional production systems, the 4RLB treatment in wheat exhibits the greatest potential. Grain yield was only reduced 23 and 15% in 2004 and 2005 compared to the check, while self-seeding was 46 and 33 plants m^{-2} in 2004 and 2005. For organic- or low-input no-tillage systems, the 4RNB treatment in wheat may offer the greatest potential because weed suppression may be enhanced and self-seeding was 24 and 57 plants m^{-2} in 2004 and 2005.

CONCLUSIONS

Winter cereal cover crops overlapping with soybean can self-seed, although species and management affect the extent of self-seeding. Using a combination of mechanical control and a late herbicide band over the soybean row was the least competitive system in this study and shows the greatest potential for adoption in conventional production systems. The four-row system using only mechanical control provides weed suppres-

Table 7. Winter cereal cover crop species and management system effect on self-seeding plant density in November 2004 and 2005 near Ames, IA.

	2004				2005			
Management†	**Wheat**	**Triticale**	**Rye**	**Mean**	**Wheat**	**Triticale**	**Rye**	**Mean**
	no. m^{-2}							
Four-row, early band (4REB)	22	4	4	10b‡	66a	16b	1b	28
Four-row, late-band (4RLB)	46	8	4	19b	33b	14b	5b	17
4-row no-band (4RNB)	24	7	6	12b	57a	12b	1b	23
Two-row band, no-chop (2RBNC)	68	40	52	53a	57a	58a	49a	54
Two-row band (2RB)	40	8	5	18b	36b	8b	7b	17
Mean	40a§	14b	14b		50	22	12	

† Two or four 19-cm rows between each 76-cm soybean row and mechanical control in all treatments except the 2RBNC using a rolling stalk chopper.
‡ Means followed by the same letter within a column are not different at $P = 0.05$.
§ Means in 2004 followed by the same letter within a row are not different at $P = 0.05$.

sion and is probably best suited to no-tillage organic production systems. Additional research addressing the agronomics of these systems including cover crop seeding rate, timing of mechanical control, cereal and soybean cultivar selection, self-seeding cover crop seed viability, and seed dispersal are needed to develop less competitive self-seeding systems.

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